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Experimental assessment of mechanical behavior of a compressed stabilized earth blocks (CSEB) and walls

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ABSTRACT

The use of compacted stabilized earth blocks (CSEB) in load-bearing masonry is largely developed during these last decades. This paper reports on an experimental study of the chemical and mechanical stabilization effects on the compressive strength of earth blocks and triplet/walls. The blocks prepared with a high sandy soil mixed with rising cement and/or lime contents and compacted at 7 MPa are tested in uniaxial compression. The triplet and walls built with these CSEB units were joined with a cement/earth mortar.

Static uniaxial compression tests are typically undertaken on samples of earth mortars, on single earth blocks, on triplets of blocks with and without mortar, and lastly on masonry specimens made of CSEB. Compression tests were performed on CSEB blocks and mortar by using a video extensometer for accurate contactless strain measurement. Mechanical parameters were thus determined, including compressive strength, Poisson's ratio, and elastic modulus. The results show that the compressive strength values of earth blocks treated with stabilizers were generally increased by rising the additive content. The increase of earth/cement blocks resistances was found more marked in comparison with those of earth/lime. It was also observed that the blocks prepared with an optimal content of lime along with cement have led to continuous increases of mechanical strength up to values greater than 5 MPa. The relationship between the blocks and triplets' compressive strengths as a function of stabilizer content (cement/lime) is linear. In the range of cement content from 6 to 8 %, the compressive strength of triplets is respectively 16 % and 20 % higher than those of walls. The observed failure of triplets and walls occurred essentially by the propagation of vertical and diagonal cracks

1 Introduction

Earth construction is considered as the widespread solution for residential housing in a large rural area around the world, due to locally available materials and relatively simple construction methods. However, a rapid deterioration of the materials under harsh weather conditions is pointed out as the main drawback. To overcome this disadvantage, the physical and hydro-mechanical properties of the wall unit or block should be improved. Substantial attention has been paid to the experimental determination of the compressive strength which is considered the most important parameter to evaluate the load-carrying

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ability (Walker [1], Bahar et al. [2]). The enhancement of mechanical properties of earth block is generally performed in three possible ways: mechanical, physical, or chemical stabilization (Walker [3], Bui[4], Harjinder et al. [5]). The mechanical stabilization consists of applying compacting stress to reduce the surface porosity of the blocks and consequently enhance their resistance, whereas chemical stabilization is based on mixing binders with the soil.

Generally, cement and/or lime are the most used stabilizers in earth constructions. Various studies have focused on the use of adding cement in order to increase the strength of CSEB's. However due to the energy-intensive nature of cement production, it is used optimally in the manufacture of earth blocks (Houben et al. [6]).

The amount and the type of binders depend on the soil's characteristics and economical considerations. For instance, in the aim to avoid block friability, it is recommended to use more than 5 % of cement (Walker [3]). As reported by Vankatarama and Gupta [7] injecting 6 %, 8 % and 12 % of cement influences significantly the compressive strength, the stress-strain and the elastic properties of the cured earth block. The stabilization by lime could also improve the mechanical and hydrous properties of CSEB as demonstrated by Guettala et al. [8]. More adapted for clayey soil, the lime imparts a long-term strength gain to earth (Bell et al. [9], Herrier et al. [10]).

The use of lime and cement has been also studied by Burroughs [11] in order to overcome the problem resulting from drying shrinkage. Furthermore, Nagarej et al. [12] pointed out the mutual benefits of admixture of cement and lime in imparting strength to the blocks.

Earth masonry construction can be subdivided into two distinct categories, mortared masonry, and dry-stacked masonry. The most common type of dry-stacked earth masonry is referenced to use earth blocks stabilized with cement and compacted mechanically (Jase et al. [13], Hongwang et al. [14]). Bei [15] studied the shear bond strength between compressed earth blocks and mud mortar interface in comparison with that of fired blocks and lime mortar. As parameters, geometrical aspects of the prisms such as the joint thickness, the blocks width and the mortar composition on the shear behavior of the masonry prisms were investigated.

Walker[1] reported on adhesive strength developed between cement stabilized earth blocks and mortars. Suitability of differing mortars was assessed on the basis of mortar workability and bond strength developed between blocks. In general, this study recommends using soil: cement mortar based on the same soil mix as the block and stabilized with 5% cement. However, higher cement mortars may be warranted when greater shrinkage is anticipated, for example, with mortars using soils with clay contents exceeding 15–20 %.

The utilization of CSEBs in load-bearing masonry poses naturally a scale-transition problem from blocks to wall in the assessment of the mechanical properties. It is worthwhile to notice that the relationships between the compressive strength of blocks, triplets and walls are not sufficiently studied. From the literature, the triplet resistance in compression represents 50 % to 95 % of earth block compressive strength (P'kla [16]). This fluctuation depends on the type and amount of the stabilizers, the compacting energy of the blocks and the presence or not of a vertical joint in the triplet. The influence of mortar used for the joint is important for wall construction. Under compression, the wall and earth block mechanical behavior is nearly similar as reported by Zine-Eddine et al. [17]. Furthermore, the behavior of the CSEB walls and the conventional masonry, notably their failure mode, is similar (Walker [3]). The compressive strength of the walls represents 1/3 of earth blocks ones, whereas their difference between the cracking and nominal failure loads approaches30 % as pointed out by Olivier [18]. A plastic field in the constitutive law of the unstabilized walls under uniaxial compressive loading is not observed.

Other experimental results evidenced how the global performance of earth block masonry elements is mainly governed by the non-linear behavior of constituent materials (Miccoli et al. [19-20]). For this purpose, axial compression and diagonal compression tests were carried out, which allowed determining important mechanical parameters, such as compressive strength, Young's modulus, Poisson's ratio, shear strength and shear modulus.

Jayasinghe and Mallawarachi [21] explored the lateral flexural capacity of CSEB walls using four types of blocks of different shapes with 5 % of cement content. Testing results showed that the predominant failure mode of all 4 types of walls was brittle tensile cracking. Laursen et al. [22] investigated the potential to improve the current design practice to make this a safer construction form. Five (05) CSEB walls were built according to current design practice in Indonesia and Thailand are subjected to out-of-plane loading. Two walls were full-scale panels and the remaining three walls were 1.1 m tall. Results from the experiment showed that the CSEB walls were relatively flexible, mainly due to slack in the dry-stack joints.

In the present study, the influence of mechanical and chemical earth stabilization on the compressive strength of block is investigated. Effects of binders such as cement, lime and cement/lime mixes used to impart strength gain to CSEB are studied. A contactless measurement technique by using a video extensometer for the determination of mechanical properties of blocks and mortars is applied. This technique relies on some (non-contact) measurement of the strain with marker tracking and area variation. Furthermore, the paper treats the relationship between the compressive strength of (mortared or not) triplet and wall built with the differently stabilized blocks.

2 Materials and preparation

2.1 Soil composition

The soil used in this study was sourced from an area located in the coastal Algiers region (Souidania). The earth blocks were prepared by using a high sandy soil as revealed by the mineralogical compositions listed in Table 1. The mineral characteristic is typical of homogenous earth composing, with a significant presence of quartz, whereas the clayey phase is represented by Illite and Kaolin. The soil contains 14 % of clay, so within the range recommended by Houben et al. [6] and CNERIB [23].

Table 1. Mineralogical composition of soil

Minerals	Mineralogical composition (%)
Quartz	74
Kaolinite	10
Illite	04.50
Calcite	02
Albite	02
Feldspaths	03
Ferruginous minerals + background RX	04.50

2.2 Soil preparation and stabilization

Before mixing, the excavated soil was immediately dried on exposure to the sun, then crushed, and finally passed through a 5 mm sieve to eliminate the large lumps. According to Houben et al. [6], the small elements of clay must be dissociated in order to avoid nodules, which affect considerably the block resistance. A static compactive method was used to select the optimum moisture content in accordance with NF P94-093 standard and local recommendations CNERIB [23]. This method provides a maximal dry density to the CSEB specimen.

Ordinary Portland cement type CEM II 32.5 and ordinary commercial lime is used to stabilize chemically the compressed earth blocks. The cement is well accommodated with low clayey and plastic soils as reported in CNERIB [24]. In addition, lime and mixes of cement/lime are also tested. The additives contents and compactive efforts studied are summarized in Table 2.

Table 2. Mixtures and compactive efforts

<table>
<tr><th rowspan="2">Compactive effort (MPa)</th><th>Cement</th><th>Lime</th><th colspan="2">Cement and Lime</th></tr>
<tr><th>Percentage (%)</th><th>Percentage (%)</th><th>Percentage of Cement (%)</th><th>Percentage of Lime (%)</th></tr>
<tr><td rowspan="3">2, 5, 7</td><td rowspan="3">0 2 4 6 8</td><td rowspan="3">0 5 8</td><td>5</td><td>3</td></tr>
<tr><td>5</td><td>5</td></tr>
<tr><td>5</td><td>8</td></tr>
</table>

2.3 Earth blocks, mortars cube and walls: preparation and testing

2.3.1 Compressed and stabilized earth blocks, triplets and walls

The different mixtures are vertically compressed by using a hydraulic machine under three different compactive efforts (2, 5, and 7 MPa). The CSEB dimensions are 29.5 cm of length (l), 14 cm of width (w) and 9 cm of height (h), figure 1-a. After being demolded, the compacted mixture was left in air laboratory until the age of testing. The required time for curing is 28 and 90 days respectively for CSEB/cement and CSEB/lime blocks [25 - 26].

For the determination of mechanical properties (stress, strain, Young's modulus, Poisson ratio) three earth specimens (ES1, ES2, and ES3) were cut from the entire block stabilized with 6 % of cement and compacted at 7 MPa of compactive effort. The cut specimens were nominally 90 mm in large, 150 mm in length and 100 mm in depth.

The triplets are composed of three CSEB units (45 cm in height). For this study, only horizontal joints were considered as shown in figure 1-b. The mortar is an admixture of earth with 12 % of cement. The tested walls were prepared by using four blocks in elevation and two blocks in width joined horizontally and vertically with a mortar (1.2 cm thick), figure 1-c. The dimensions of the walls are 80 cm x 60 cm x 9 cm. The blocks were partially saturated by soaking them in water for a period of (30 s) prior to the casting of the masonry walls. The period of cure is fixed to 28 days.

(a) (b) (c)

Fig. 1 - Fabrication earth blocks masonry walls, (a) CSEB, (b) triplets, (c) wall.

2.3.2 Mortars cubes

The mortar is made of the same earth used for the preparation of the blocks and stabilized with 15% of cement. For the compressive testing, three mortar cubes (CM1, CM2, CM3) with the lateral dimension of 100 mm were prepared.

2.4 Determination of the mechanical properties of compressed and stabilized earth and mortar

The compression tests on blocks were carried out by using a hydraulic press with 1000 kN capacity. The test was run at a constant displacement rate of 0.02 mm/s. The imposed displacement to the bottom platen and the associated load are automatically recorded.

The compression load on mortar cube is applied with a displacement control rate of 1.2 mm/min, and this perpendicularly to the direction along which they are normally compacted, figure2.

Fig. 2- Mortar cube compressive strength

Strains on the specimen surfaces during different test procedures are determined from surface displacements obtained from a full-field optical technique known as video extensometer (FVX), figure3.

FVX uses a mathematical correlation method to analyze different digital images of a specimen surface, taken during the test, that correspond with different stages of loading (Miccoli et al. [20]). This technical method of measurement was used to investigate the mechanical properties of blocks and mortar by applying a displacement of points from surface samples and relate it to the response obtained from the compressive force. Surface point displacements during this test are obtained via digital image correlation by using FVX extensometer video. Another study conducted by Rekik et al. [27] used also the Digital Image Correlation method (DIC) to examine the compressibility of dry joints. Compressive tests on specimens were carried out. Tests were conducted using an accuracy of 0.2 % of the attained load and 0.033 mm/min displacement rate. A two dimensional (2D) Digital Image Correlation is utilized to measure the compressive behavior of the dry joint.

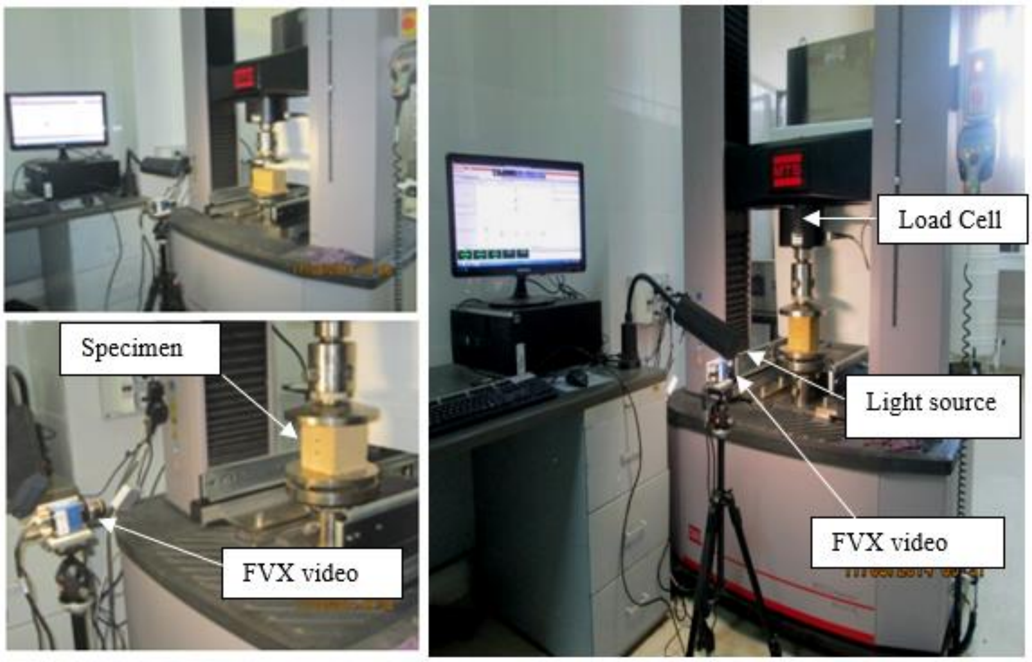


Fig. 3- Experimental setup Video extensometer (FVX)

The advantage of this technique when compared to strain measurements with gauges or LVDT is to measure longitudinal and transversal deformations without contact with the sample and consequently without any perturbation phenomena, by real-time image analysis. The points on the images correspond to the useful area of deformation measurement at each loading level. Each image represents a state of deformation, as shown in figure 4. The calibration process starts with the system comparing the pixel coordinates of detected reference points to their real-world coordinates calculated from dot spacing. These measurements were output as a text file and analyzed using statistical tools in the software FVX.

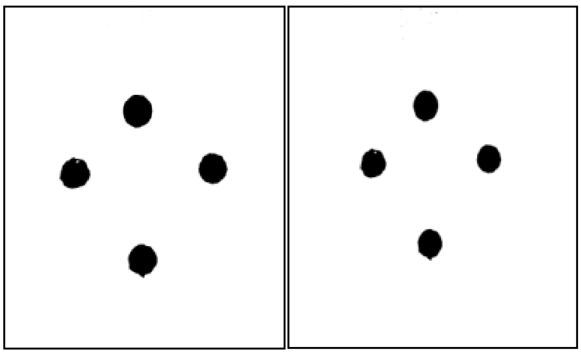


Fig. 4-Technical correlation images

2.5 Compressive strength tests on triplets and walls

Triplets with and without the presence of mortar between the block-to-block interface were subjected to uniaxial compressive loading, see figure 5. The triplet elements are taken from the same production used (Block and mortar with respectively 6 % and 15 % of cement).

Fig. 5- Triplet (block with 6 % of cement): Compression test at failure.

The experimental setup used for the determination of the compressive strength of walls is shown in figure 6. The compression tests on walls was carried out using a hydraulic press with 2000 kN capacity. The test was run at a constant displacement rate of 1.25 mm/min. After covering the top with a hard mortar (earth cement admixture) in order to reduce the impact of fretting between the walls and the loading plates, a stiff steel beam is placed on top of the walls to uniformly distribute the vertical load of the actuator (planeness defect).

(a) (b)

Fig. 6- Compressive strength test on CSEB walls, (a) CSEB 6 % cement, (b) CSEB 8 % cement.

3 Results and discussion

3.1 Compressive strength of CSEB

Table 3 shows the result of the block's resistance values versus additive contents. Generally, the compressive strength of the blocks increases with the increase of the stabilizer content. Furthermore, the evolution of the compressive strength values of the CSEB/cement blocks is more marked than the CSEB/lime ones. Indeed, for the same additive content, the imparted gain by using cement exceeds 4 times the unstabilized earth blocks resistance, whereas this ratio is less than 2 for earth/lime blocks. These findings are in accordance with the previous works (see for instance Nagaraj et al. [12]). Moreover, the combination of cement and lime enhances the block resistance. In particular, adding 8 % of lime instead of 5 % (with 5 % of cement) imparts to the block a resistance gain of 2.4 MPa with the highest compaction level.

As set out in the literature, an ascending trend of the compressive strength as the compacting energy increases is highlighted. This influence becomes more important as the stabilizer amount is increased. However, this gain in the compressive strength did not emerge from the CSEB/lime blocks. The values of the compressive strength of these blocks in a dry state are still less than those indicated in the standard recommendation, respectively 6 and 5 MPa (CNERIB [23]).

The results show also a convergence between the evolutions of the compressive strength of cement and cement/lime admixture, where the block resistance value reaches 8 MPa. Guettala et al. [8] obtained similar results when using 8 % of cement content, which is considered as a good quality/price ratio for earth blocks.

Table 3. Results of the CSEB compressive strength

	Cement (c)					Lime (l)			
Compaction (MPa)	**0 %**	**2 %**	**4 %**	**6 %**	**8 %**	**5 %**	**8 %**	**5% c +5 % l**	**5 %c +8 % l**
2	0.6	1.50	2.65	3.70	4.18	1.25	2.32	3.85	3.70
5	1.8	1.9	3.8	6.26	7.17	2.15	3.2	5.1	5.4
7	1.90	2.11	4.44	7.38	8.13	2.66	3.50	5.70	8.10

Figure 7 presents the strain-stress curves of the CSEB for the different stabilizers. The continuous compression is applied along the block width direction. The shape of the curve in compression is parabolic. The strain-stress curves could be divided into two parts: the pre-compression stage and the real-compression stage. The lower level of strain at the strength peak is around 0.4 %. Stress–strain curves usually showed a yield point where the blocks start to slide gradually until friction set in. The blocks exhibited a brittle failure in a short time after reaching their maximum compressive stress. The ultimate vertical strain is varying between 0.4 % and 0.5 % and usually exhibits an abrupt failure. However, the blocks treated with cement (6 and 8 %) have residual strengths and more deformation capability.

The elastic modulus increases by 1.72 times when the cement content is increased from 6% to 8 %. This ratio is still under the enhancement level of the elastic modulus reported by Venkatarama and Gupta [7]. In their study, by rising the cement content from 6 % to 8 %, the elastic modulus of the earth block is multiplied by 2.5. In the case of the mixed composition, a ratio of 1.4 is obtained when rising the lime content from 5 % to 8 %. However, for the blocks treated only with lime, no increase in modulus of elasticity is observed (figure 7-c).

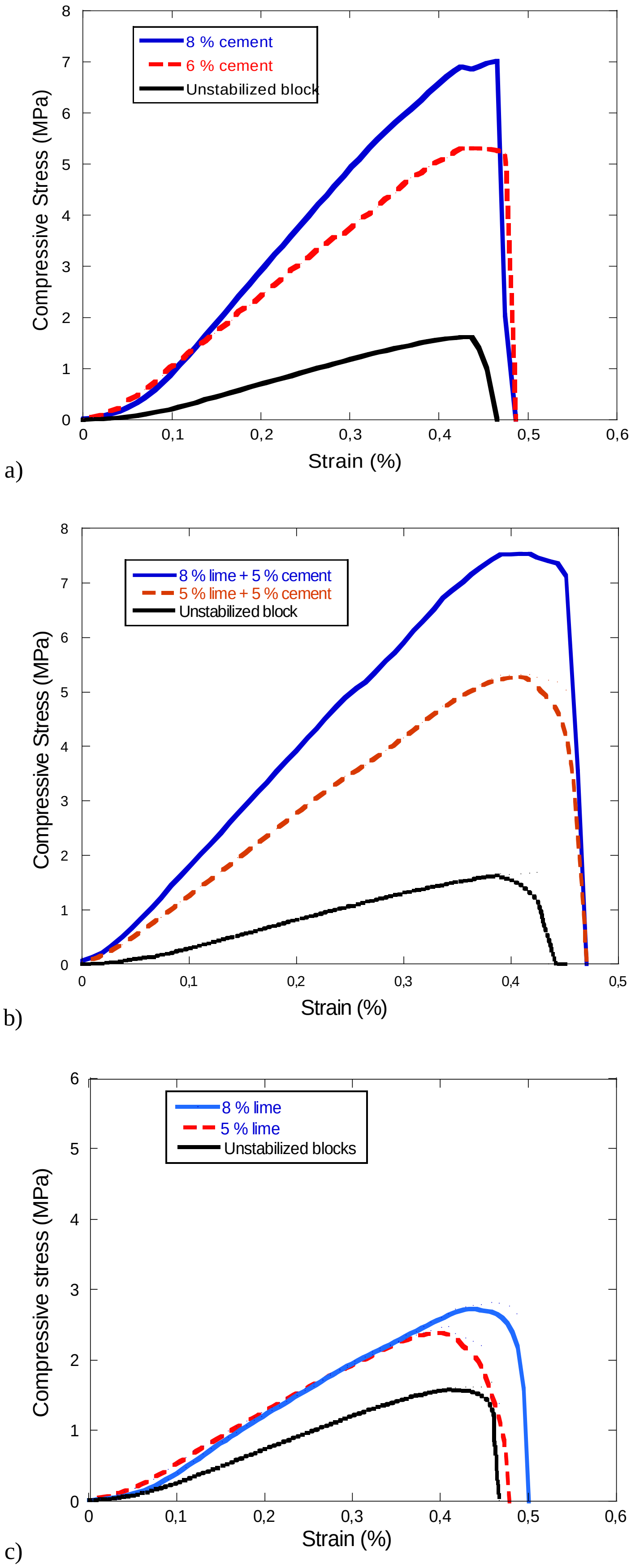
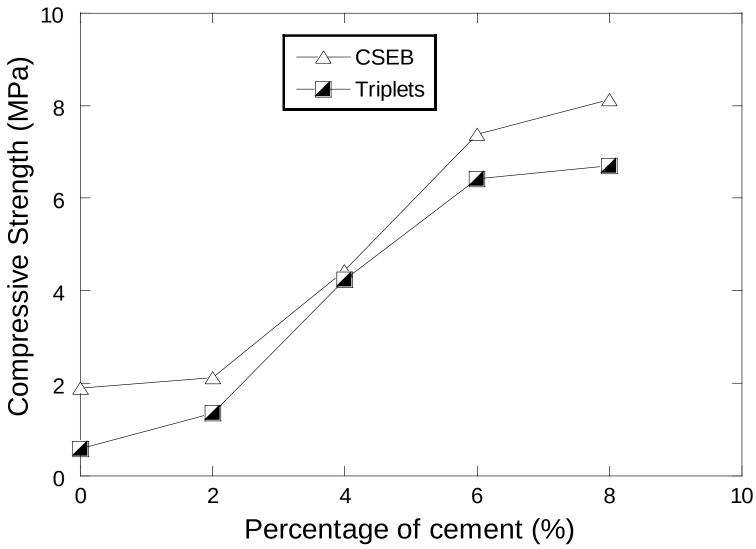


Fig. 7 - Stress-strain relationship of the tested compressed earth blocks, stabilized with cement (a), cement+lime (b), lime (c).

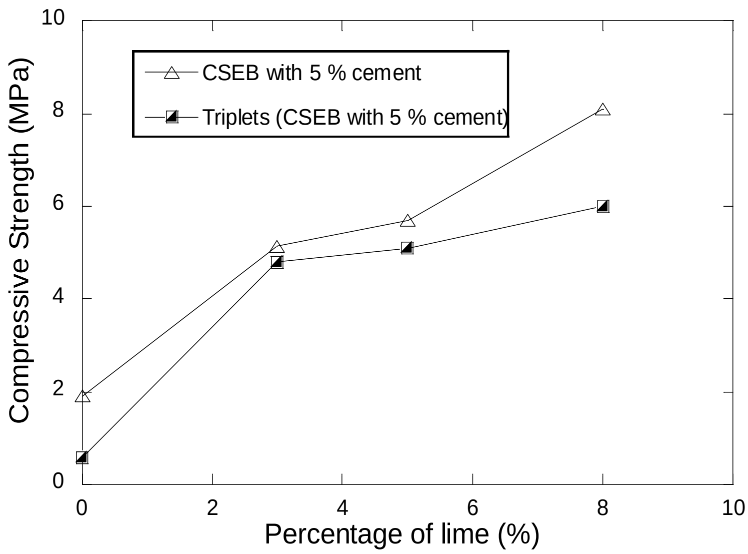
3.2 Compressive strength of triplets with the differently stabilized blocks

The figures 8-a and b show the evolution of the compressive strength values of CSEB and triplets built with these blocks as a function of the different stabilizers (cement, lime, and cement/ lime), under a compactive effort of 7 MPa.

The results show that the triplet resistance is systematically enhanced as the binder content is increased. Thus, rising the cement content in the CSEB from 4 % to 8 % confers to the triplet resistance an enhancement of around 58 %. In addition, as the cement content exceeds 4 %, the resistance discrepancy of the CSEB and the triplet is reduced. As depicted in figure8-a, the resistance of the triplet represents 86 % of that of their (at 6 %) cement stabilized blocks, and this triplet resistance drops to only 30 % for unstabilized constitutive blocks. The same evolution trend is observed for blocks stabilized with mixed additives. Concerning the other type of stabilizers, and as illustrated in figure 8-b, rising the lime content in the CSEB from 5 % to 8 % (with 5 % of cement) induces an enhancement of about 17 % of the triplet resistance. However, the increase of the lime content (from 5 % to 8 %) leads to a significant gap between the CSEB and the triplet resistances. For instance, at 5 % and 8 % of lime content, this difference reaches respectively 0.6 MPa and 2.1 MPa.



(a)



(b)

Fig. 8- Influence of stabilizer content on block and triplet compressive strength for (a) cement, (b) lime added to 5% of cement

A linear correlation between the compressive strength of the blocks and triplets is highlighted (as depicted infigure9). This relationship was derived only from experimental data of triplets prepared with cement stabilized blocks (at 2, 4, 6 and 8 % content) under a compactive effort of 7 MPa. The strength relationship between block/triplet is strongly linear over the entire experimental range. This outcome confirms the conclusions obtained by Bei [15] on the compressive strength of singular specimens in CSEB blocks, which are higher than those of triplets with an average of around 50 %. The results are also in accordance with the outcomes by P'kla [16], the enhancement of compressive resistance of the blocks and triplets coincides with increasing cement content, where the ratio between the compressive strength of the triplets and those of the blocks is between 0.5 and 0.95. Similar results were also obtained by Zin-Dine et al. [17].

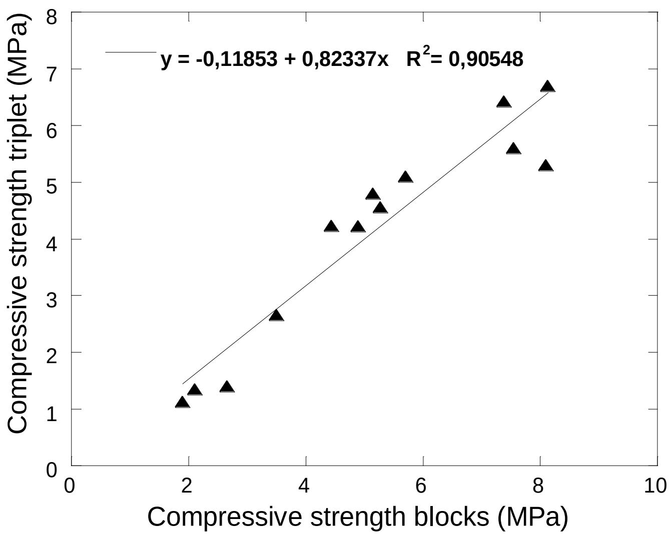


Fig. 9- Compressive strength of triplets as function of compressive strength CEB stabilized with cement

3.3 Mechanical characteristics of blocks and mortar

The elastic modulus, Poisson's ratio, and compressive strength of the block and mortar were obtained from different tests. The mortar was prepared from the same batch of earth used to produce the block. These values are reported in Tables 4 and 5.

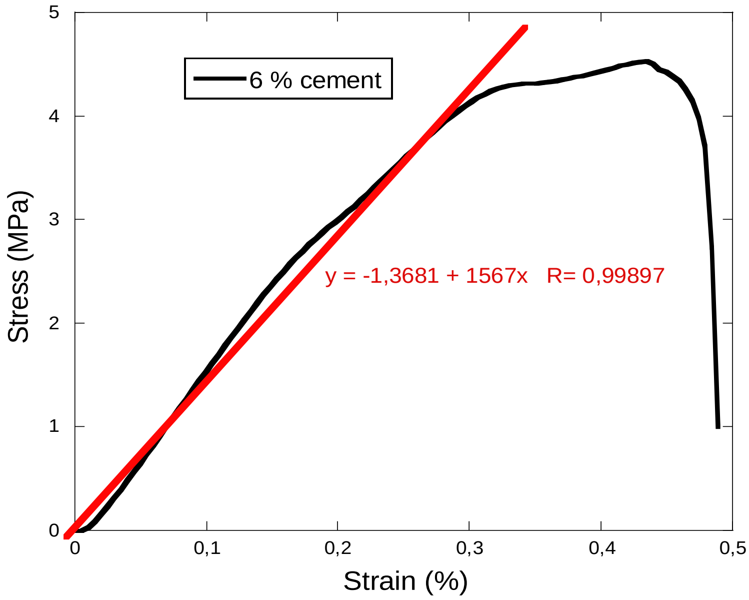
Table 4. Mechanical properties of blocks

Bulk density ρ (kg/m^3)	Modulus of elasticity E (MPa)	Compressive strength f_{CSEB} (MPa)	Poisson's ratio μ
1800	1500	5,80	0,21
1800	1500	5,80	0,21
1820	1570	6,00	0,22

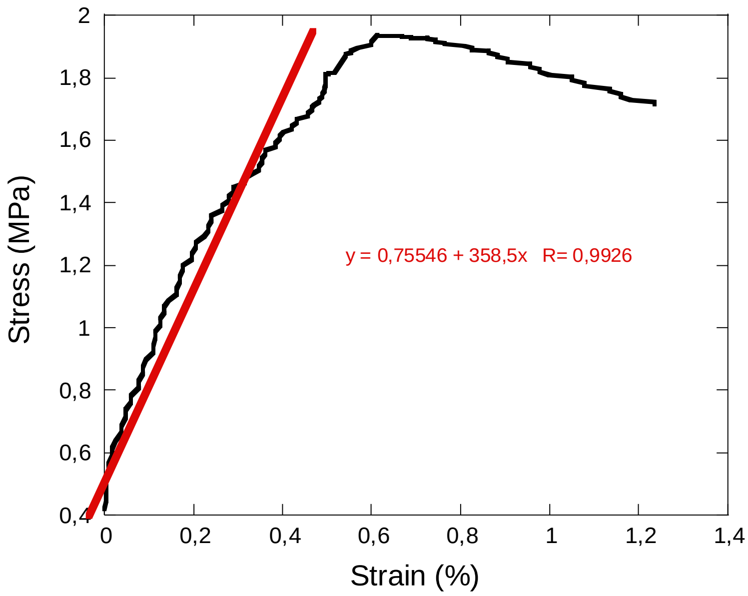
Table 5. Properties and mechanical parameters of mortar

Sample	Bulk density ρ (kg/m^3)	Modulus of elasticity E (MPa)	Compressive strength f_{cm} (MPa)	Poisson's ratio μ
CM1	250	350	1,90	0,18
CM2	255	360	2,00	0,19
CM3	255	360	2,00	0,19

The figures10-a and b show respectively the stress-strain curve of the mortar and the block. As illustrated, the recorded behavior can generally be divided into three distinct phases. Initially, a contact adjustment phase occurs, during which the loading is redistributed. In the second phase, the progress of the loading process leads to a substantially increased derivative of the stress–strain curve, until the maximum stress is reached. This phase includes a stress range over which deformations tend to increase linearly. Using the stress–strain data obtained from CSEB blocks in the aforementioned linear range, Young's modulus (E) of 1500 MPa is determined. After the maximum load-bearing capacity is exceeded, the material is subjected to compression softening, up to the ultimate strain sustained. Similarly, the initial tangent modulus of mortar sample was derived from the graph slope. An average value of 350 MPa of Young’s modulus was found.



(a)



(b)

Fig. 10- Stress vs deformation curves for CSEB (a) and mortar (b) tested in compression

At maximum compressive stress, comparatively to mortar specimens, a CSEB is subjected to brittle behavior with less deformation before the collapse. This can be interpreted, to some extent, by the role attributed to the mechanical stabilization of the blocks by compaction, which increases the mechanical strength of the blocks (Mahdad et al. [25]).

Compressive failure of mortar and CSEB blocks were characterized by bulging and formation of near-vertical surface cracks, figure 11. This failure is identical to those found in the previous experiments of Gonzalo et al. [29]. Similar results were also obtained by Bland et al. [28]. The compression force used to compress the blocks in fabrication also appears to play a role. Tests performed by Walker[30] on blocks with similar clay content and cement soil ratio, but compressed to only 2.0 to 4.0 MPa during fabrication, given dry compressive strengths of approximately 5.0 MPa, compared to the blocks tested in this work which were exposed to 7 MPa during fabrication and exhibited compressive strengths closer to 6 MPa.

Fig. 11 - Typical modes of failure in uniaxial compression for (a) mortar, (b) CSEB specimens.

3.4 Characterization of the triplet's behavior under compression

In this part, the influence of the mortar on the mechanical behavior of the triplets under compression is described. Figure 12 shows respectively the stress-strain curves of the triplet with and without mortar. Initially, the two curves of the triplets begin with a linear part, and then from a certain threshold, the decrease of compressive stress appears, which corresponds to the decrease of rigidity, caused by the blocks/mortar fracture or blocks failure.

The stress-strain curve in figure 12 remains linear up to a stress value of 3.44 MPa which corresponds to a deformation of 0.47 %. This stress value is about 21 % lesser than the maximum stress found in the mortar less triplet. In this case, under compression, the strain of the mortar less triplet is about 27.6 % greater than the strain observed on triplet with horizontal mortared joints.

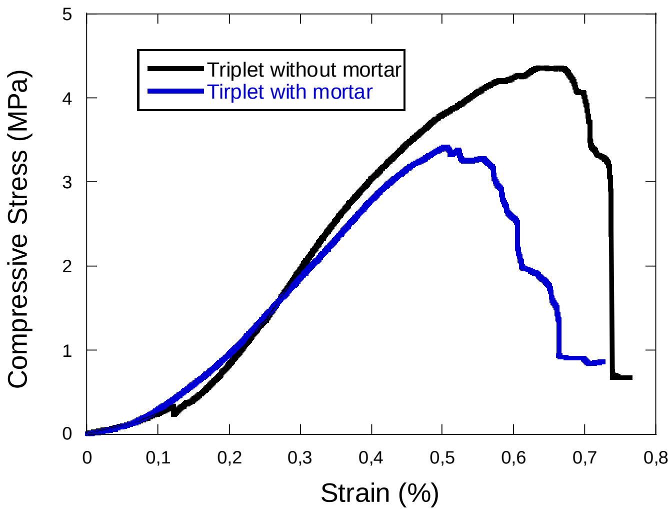


Fig. 12 - Stress-Strain curves of tested triplet with mortar and without mortar

The modulus of elasticity (E) of the two triplets is determined by the linear elastic part of the stress-strain curve. The deformation of the triplet without mortar is more than compared to the triplet with mortar, which resulted in a relatively high Young’s modulus of 1200 MPa. Furthermore, the result shows that by adding the mortar, the average Young modulus of the masonry is equal to 900 MPa. This modulus of elasticity is still higher than those obtained for rammed earth panels under compression (Jayasinghe et al. [21]), which are in the order of 500 MPa.

In order to study the behavior of the triplets with or without mortar under a uniaxial compressive force, it is necessary to compare the deformation of the element at the post-peak. This comparison will be based on the value of the deformation at the decrease of the maximum force. For triplets with mortar, the difference between the deformation at the peak and after a 50 % fall of the maximum force is estimated at 8%. Similarly, this ratio is about 2 % for the triplets without mortar. The results show that the addition of mortar to the triplet increases the ductility of the material. In contrast, the introduction of mortar tends to significantly decrease its compressive strength with a ratio of 20 %. The triplets jointed with mortar develop ductile behavior compared to the triplet without mortar that followed the behavior of the blocks, which is brittle. This means that whatever the mortar has a compressive strength equivalent to 2/3 of the compressive strength of the earth block, the contact between the two materials was a weak point regarding the overall behavior.

3.5 Failure mode of the triplets

Figures 13 (a)-(b) illustrate the testing setup and typical failure of CSEB triplets. The observed failure mode is the one typical reported for triplets subjected to compressive loads. The first damages of the triplets appear at the joints, which are gradually crushed under the compression force. Subsequently, vertical cracks with progressive openings affect the middle block along its entire length. At the onset of the failure, these vertical cracks are less than 2 mm in width. Furthermore, and as presented in figure13, the diagonal cracks also appear around the edges of the sample. This failure mode suggests also that the block units have failed by shear before they can develop their full compressive capacity. This result corroborates the findings of Ben Ayed et al. [31], who observed in their experimentation a stress concentration between the clearance of the two and the three stacked blocks. Afterward, the compression zones formed at the top corners broke off and the block was gradually dislocated until total collapse. The typical failure mode also observed in masonry walls subjected to vertical compression is a vertical split through the thickness of the walls (CNERIB, [23]).

a)

b)

Fig. 13- Crack patterns for triplets, with (a) and without (b) mortar

The compression tests on triplets (without mortar) indicate that the onset of failure is characterized by the formation of a vertical crack (less than 2 mm) parallel to the axis of loading along the mid section of the triplet. Failure did not occur at the joints but, in almost all cases, at the block-interface, as illustrated in figures13 (a)-(b). This crack running down suggests the possibility of stress concentration around the midsection. At the ultimate state, cracks also appeared on the faces and edges of the specimen.

The line of a crack running vertically along the edge of the triplet is similar to that experienced by the block unit. The same observations were found by Bei [15]. Singular triplets solicited in uni-axial compression developed vertical cracks throughout the sample as the maximum load is approached.

3.6 Mechanical behavior of walls

An example of the failure patterns of the walls is illustrated in figure 14. The compressive strength values are about 3.15 MPa and 4 MPa for walls built respectively with CSEB at 6 % and 8 % cement content. The results show that the compressive strength values of walls represent 49 % to 59 % of the triplet resistances. Thus, the smaller the size of the masonry the stronger and stiffer is its behavior. In addition, as illustrated in figures 14 (a) and (b), the damages can be localized onto the masonry unit, in a mortar joint as well as at the interface between masonry unit and mortar joint.

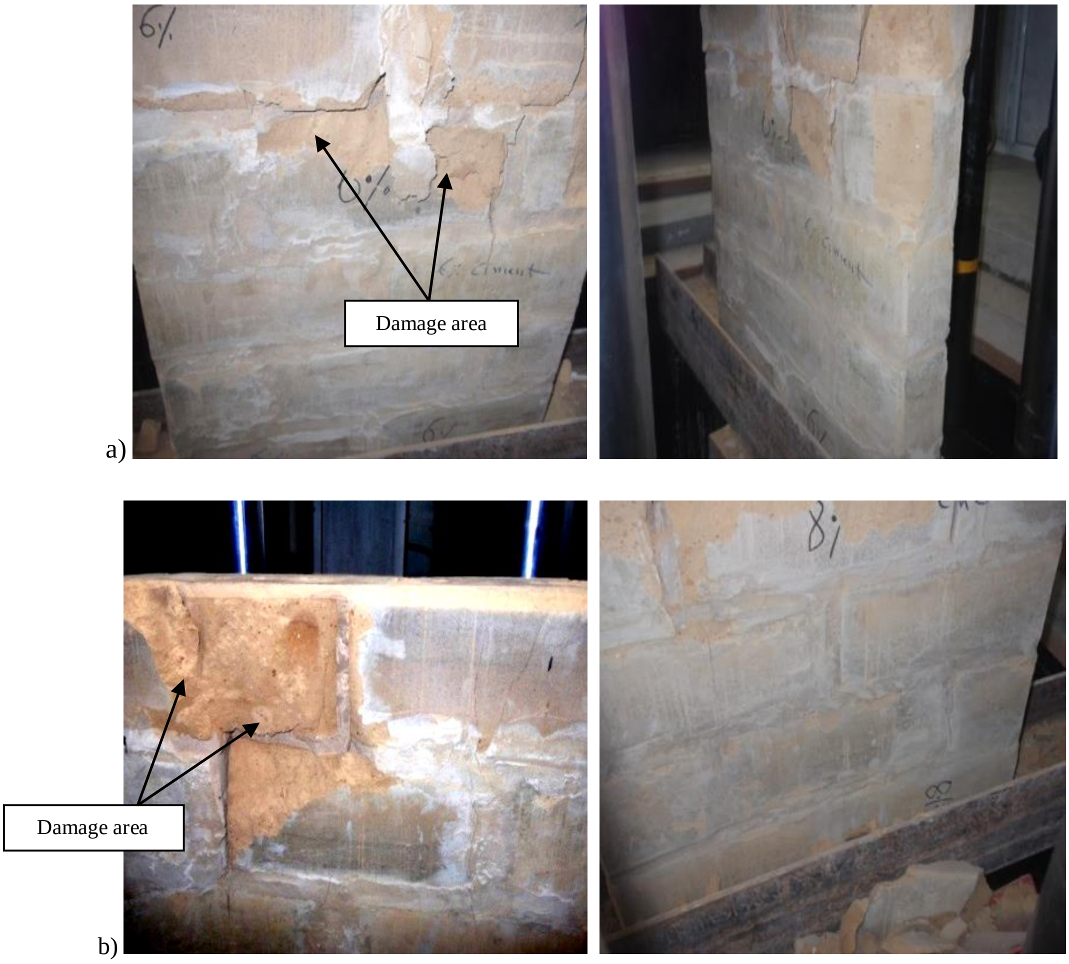


Fig.14 - Typical failure mode of mortar bound CSEB masonry walls under uniaxial compression, stabilized with 6 % (a) and 8 % (b) of cement.

Masonry walls started to develop cracks much earlier before the ultimate load of the wall. This characteristic behavior of masonry is attributed to the interaction between the blocks and mortars joint (P'kla [16]). Cracking is the most current type of damage observed on earth blocks masonry structures. The mode of failure (through vertical cracking) is typical for walls subjected to compressive loads. The crack can be either perpendicular through head and bed joints or pass through units and head joints in the CSEB walls. This type of failure implies continuous cracks through blocks units and head joints. Afterward, at the peak load, the splitting of the blocks is observed.

This trend generally agreed is that the strength of the CSEB walls depends on many parameters, such as masonry units/blocks geometry, the strength of the mortar, joint arrangement, and even from the workmanship. This experimental statement is in accordance with the failure mode reported by Miccoli et al. [20], who observed also that the stress-strain curve of the CSEB walls tested exhibits a short phase of post-peak strain softening, due to its brittle behavior under uniaxial load. Related to this type of test, similar results have also been achieved by Miccoli et al. [19]. Strength values were in the range of 2.0–3.7 MPa. The height/width ratio plays a role in the final compressive strength value. As reported by Bei [15] for doublets and triplets specimens, the failure seems to be more akin to that observed in the masonry wall under uniaxial compression. The results found that the height/width ratio plays a role in the final compressive strength value.

4 Conclusion

This paper presents a set of experimental results obtained from a recent investigation devoted to the improvement of the mechanical characteristics of earth wall units by compaction and chemical stabilization, by using different contents of cement and/or lime. Compressive tests on triplets with and without mortars and walls with differently stabilized blocks are also carried out. The main conclusions which are drawn and revealed that the block resistance is globally enhanced by increasing the stabilizer content. The impact of the compactive effort is more significant for earth blocks stabilized with cement than for lime mixes. Thus, the stabilization by mixing cement and lime also imparts a non-negligible strength gain to the CSEB.

The compressive strength and Young's modulus of the CSEB masonry can be determined indirectly through the compressive strength of the small blocks or prisms or through the flexural strength of the blocks. The elastic modulus increases by 1.72 times when the cement content is increased from 6 % to 8 %. Whereas, for the mixed composition of earth blocks, a strength ratio of 1.4 is obtained when rising the lime content from 5 % to 8 %. Furthermore, for triplets with mortar the mean value of compressive strength was 3.5 MPa for stabilized earth blocks-cement mortars. Compressive strength was increased by 20% when the joint thickness was removed. This was attributed to the increase of the stiffness zone between the blocks. In addition, the compressive strength values of triplets represent respectively 87 % and 82 % of their constitutive blocks stabilized at 6 % and 8 %cement content respectively, whereas they diminish to 42 % and 49 % for the walls. When the maximum compressive strength is reached in one element, stress redistribution occurs and the triplet response initiates to be nonlinear. Furthermore, the triplets as the almost the whole brittle materials fail due to the progress of internal cracks, inducing a softening behavior.

Video-based extensometry seems to be a powerful technique that can provide more information on earth blocks and mortar materials behavior. It is inferred from the results obtained that this technique based on marker tracking is significantly reliable and could constitute an effective alternative way to obtain accurate estimate of the intrinsic mechanical properties of blocks and mortars.

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